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(54) **SYSTEM AND METHOD FOR EFFICIENTLY  
OPERATING MULTIPLE FLYWHEELS**

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(2013.01)

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G05B 11/389, 11/39  
See application file for complete search history.

(56) **References Cited**

**U.S. PATENT DOCUMENTS**

3,734,222 A \* 5/1973 Bardwick, III ..... 180/165  
4,050,557 A \* 9/1977 Beneke et al. .... 192/225  
4,499,965 A 2/1985 Oetting et al.  
4,606,193 A \* 8/1986 Molina ..... 60/698  
4,680,986 A \* 7/1987 Elsner ..... 477/6  
4,999,965 A \* 3/1991 Schmidgall et al. .... 52/684

6,012,561 A \* 1/2000 Reed et al. .... 192/48.2  
6,024,667 A \* 2/2000 Krohm et al. .... 477/6  
6,029,539 A \* 2/2000 Young ..... 74/574.3  
6,435,998 B1 \* 8/2002 Sudau et al. .... 475/47  
7,108,095 B1 \* 9/2006 Washington et al. .... 180/165  
7,341,534 B2 \* 3/2008 Schmidt ..... 475/5  
7,416,039 B1 \* 8/2008 Anderson et al. .... 180/165  
7,540,346 B2 6/2009 Hu  
7,633,248 B1 \* 12/2009 Williams ..... 318/150  
8,290,653 B2 \* 10/2012 Hofbauer ..... 701/22  
8,708,081 B1 \* 4/2014 Williams ..... 180/165  
8,738,215 B2 \* 5/2014 Gibson et al. .... 701/29.1  
2003/0041688 A1 \* 3/2003 Yamazaki ..... 74/572  
2007/0179012 A1 \* 8/2007 Kimura et al. .... 475/331  
2007/0219038 A1 \* 9/2007 Druten et al. .... 475/210  
2008/0105475 A1 \* 5/2008 Hu ..... 180/65.1  
2008/0308335 A1 \* 12/2008 Anderson et al. .... 180/165  
2009/0020354 A1 \* 1/2009 Roth ..... 180/291  
2009/0182466 A1 \* 7/2009 Watanabe et al. .... 701/29  
2010/0117375 A1 \* 5/2010 Kwok ..... 290/1 R  
2010/0152984 A1 \* 6/2010 Bowman et al. .... 701/54  
2010/0184549 A1 \* 7/2010 Sartre et al. .... 475/5  
2010/0273607 A1 \* 10/2010 Winkler et al. .... 477/115

(Continued)

**FOREIGN PATENT DOCUMENTS**

WO WO 82/01519 5/1982  
WO WO 2007/138353 A2 12/2007

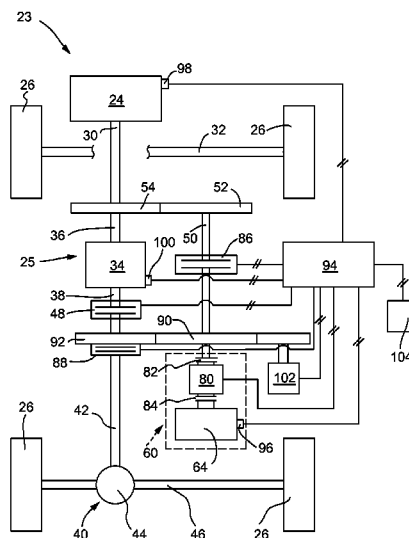
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(57) **ABSTRACT**

A flywheel assembly may include first and second flywheels having respective first and second flywheel parasitic load profiles. Operating speeds of the first and second flywheels may be selected based at least in part on the first and second flywheel parasitic loads. The operating speeds may be determined such that an aggregate of the first and second flywheel parasitic loads is minimized, thereby increasing the efficiency of the flywheel assembly.

**20 Claims, 5 Drawing Sheets**



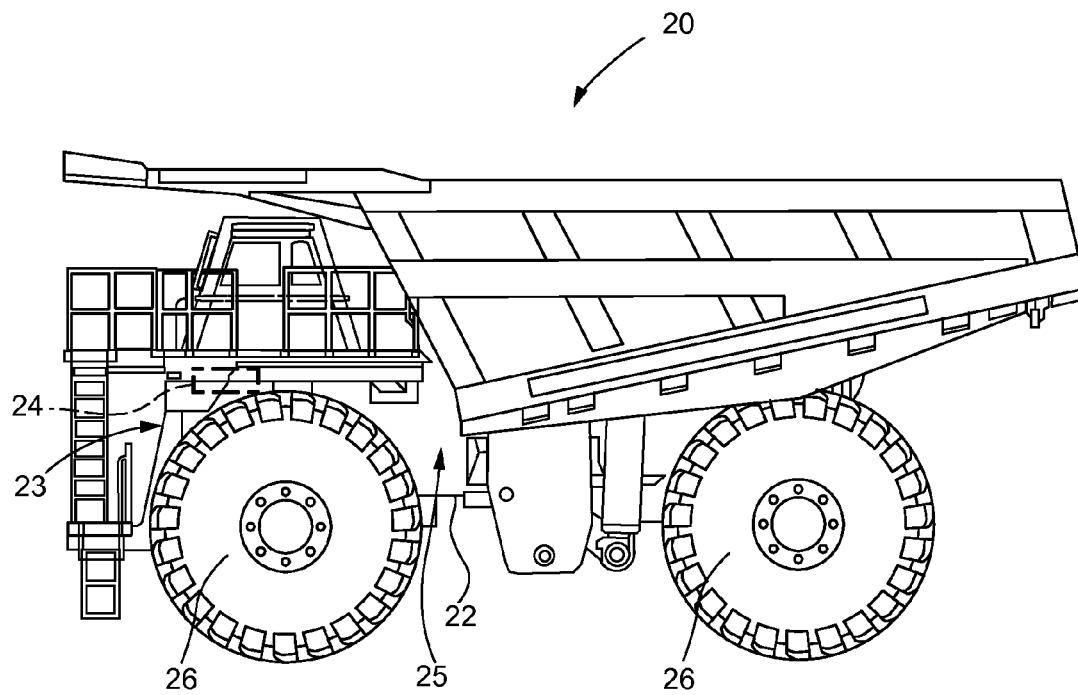
(56)

**References Cited**

U.S. PATENT DOCUMENTS

2010/0276222	A1 *	11/2010	Gramling et al. ....	180/165	2011/0175370	A1 *	7/2011	Dugas .....	290/1 R
2010/0307129	A1 *	12/2010	Chen .....	60/39.35	2011/0191013	A1 *	8/2011	Leeser .....	701/124
2010/0314168	A1 *	12/2010	Williams .....	175/5	2012/0029745	A1 *	2/2012	Miyao .....	701/22
2011/0106359	A1 *	5/2011	Tanaka et al. ....	701/22	2012/0197472	A1 *	8/2012	He et al. ....	701/22
2011/0114406	A1 *	5/2011	Gibson et al. ....	180/165	2013/0080001	A1 *	3/2013	Cousins et al. ....	701/54
					2013/0226419	A1 *	8/2013	Jensen .....	701/67
					2014/0046538	A1 *	2/2014	Siegel et al. ....	701/36

\* cited by examiner

**FIG. 1**

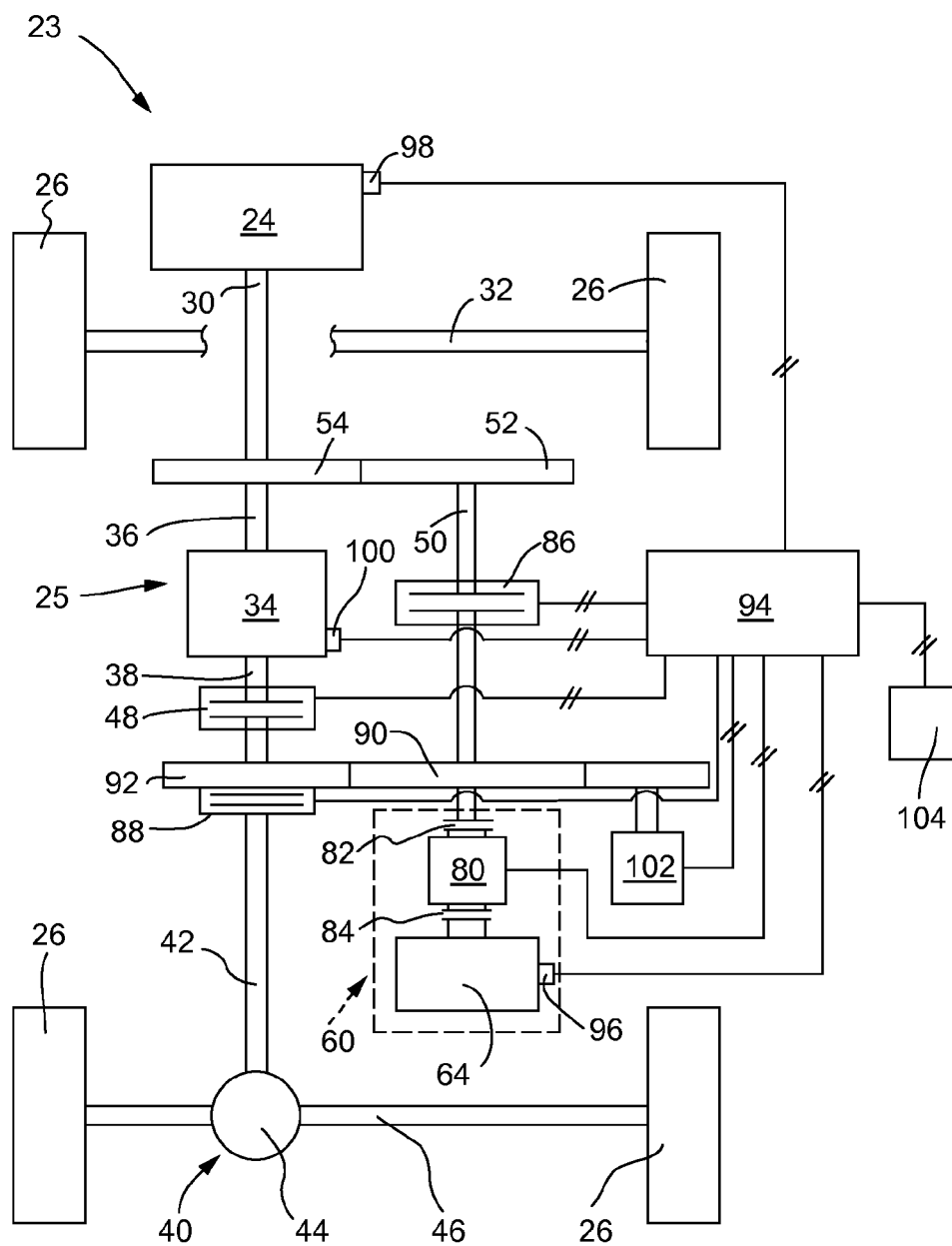
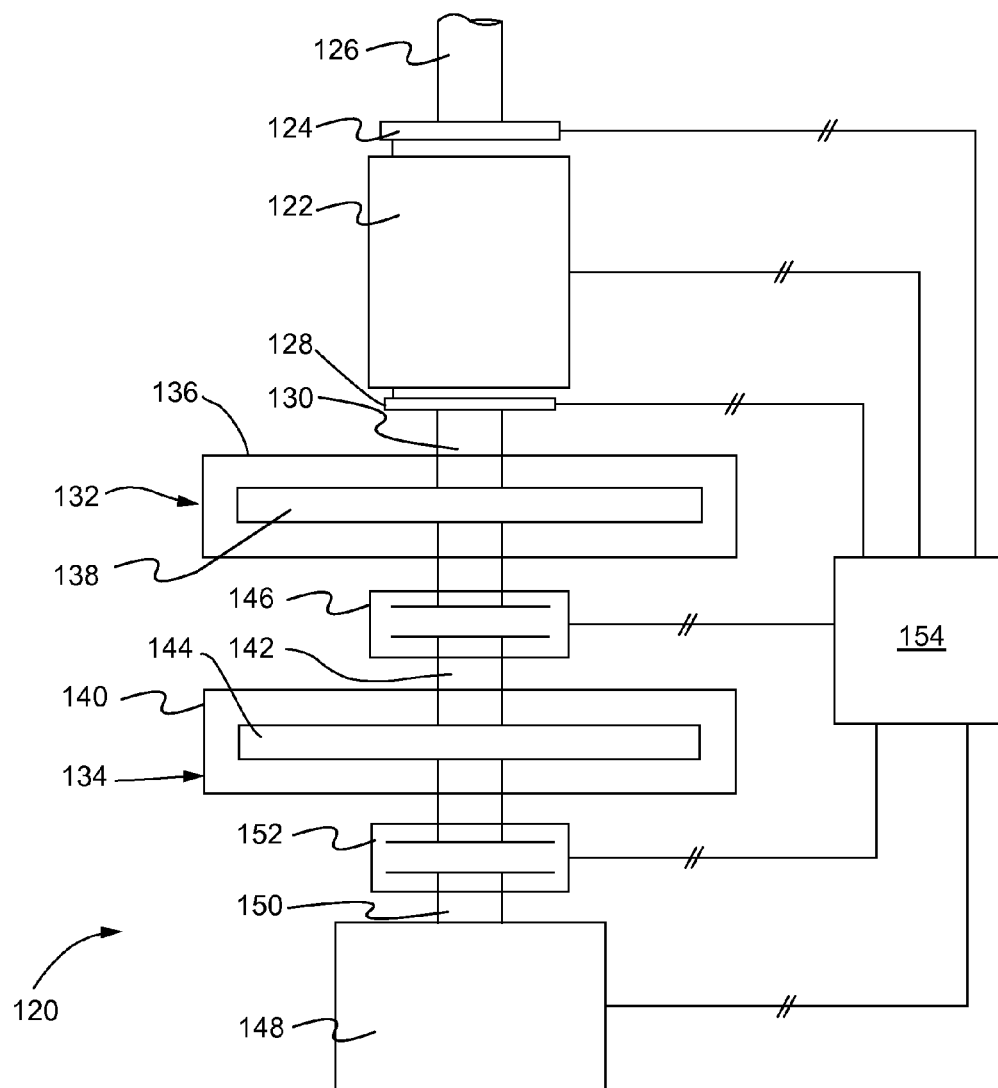
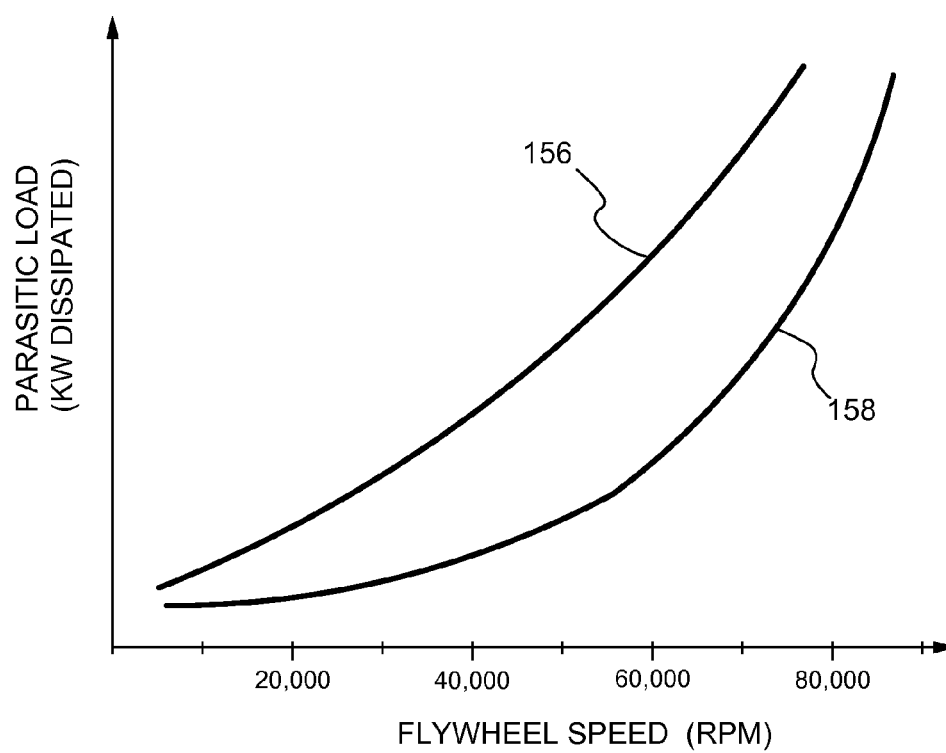


FIG. 2

**FIG. 3**



**FIG. 4**

**FIG. 5**

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# SYSTEM AND METHOD FOR EFFICIENTLY OPERATING MULTIPLE FLYWHEELS

## TECHNICAL FIELD

The present disclosure generally relates to flywheel energy storage devices, and more particularly to systems and methods for efficiently storing and deploying energy from flywheel assemblies provided on machines.

## BACKGROUND

Flywheels are generally known in the art for storing energy. While flywheel energy storage devices have been used for many years in satellite or other spacecraft applications, more recently they have been adapted for use on terrestrial machines. More specifically, hybrid power plants have been proposed which use a combustion engine as the primary mover and a flywheel as a secondary mover.

In some applications, the flywheel is operably coupled directly to an engine output, such as a crankshaft, upstream of a transmission. The flywheel may add to or subtract from power supplied by the engine to the transmission and, ultimately, one or more driven wheels. In this arrangement, the flywheel may also be configured to use regenerative braking, in which the flywheel is sped up to capture kinetic energy of the machine as it decelerates. Conversely, when the machine is accelerating, the flywheel may provide additional power to the wheels, thereby reducing flywheel speed. The position of the flywheel upstream of the transmission may allow it to efficiently spin up to a desired operating speed during start up. During regenerative braking, however, the energy from the ground engaging members may be transmitted through several mechanical connections, including the transmission, before it reaches the flywheel. Consequently, the amount of energy that can be captured by an upstream-located flywheel may be reduced by the mechanical losses as it travels through the transmission and other mechanical connections, thereby decreasing the efficiency of the flywheel.

In other applications, the flywheel may be operably coupled to a drivetrain output downstream of the transmission. When the machine decelerates, energy from the drivetrain (and an associated transmission) may be transferred to the flywheel. During acceleration of the machine, energy from the flywheel may be transferred to the powertrain to assist with the increased power demand. When positioned downstream of the transmission, the flywheel may more efficiently capture energy during regenerative braking due to the decrease in mechanical connections between the flywheel and the ground engaging members, thereby reducing the mechanical loss. During start up, however, the drivetrain may not be configured to spin up the flywheel during machine start up. Additionally, the location of the flywheel downstream of the transmission may make such spin up inefficient due to mechanical loss through the transmission.

U.S. Pat. No. 4,499,965 to Oetting et al. discloses a hybrid drive that includes both an engine flywheel and a storage flywheel. The engine flywheel is configured to compensate for non-uniformities in engine output torque, while the storage flywheel is configured to store energy during regenerative braking. Both the engine flywheel and the storage flywheel are positioned upstream of the transmission, and therefore suffer from the drawbacks noted above. Conversely, U.S. Patent Application Publication No. 2010/0152984 to Bowman et al. discloses a hybrid vehicle having a flywheel connected to a lower powertrain assembly, downstream of a

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transmission. The flywheel of Bowman et al. is not coupled to the engine, and therefore is incapable of engine-powered spin up.

The efficiency of a flywheel assembly further may be impacted by parasitic loads that resist rotation of the flywheel. Friction forces, for example, which resist the rotation of the flywheel body, are generally related to flywheel speed and environment. To reduce the impact of environmental factors, the flywheel body may be contained in a housing that is maintained at a partial vacuum pressure (i.e., substantially below atmospheric pressure) and at a reduced temperature. As a result, flywheel speed is often the primary contributing factor, and is generally proportionally related to, the amount of friction generated by the flywheel.

Friction losses may be exacerbated in more recent, high speed flywheel constructions. Flywheel bodies were conventionally formed of metal materials, such as iron and steel, which have a relatively high density that limits the speed at which such flywheels may be safely rotated before becoming structurally unstable. More recently, specialized flywheel materials have been developed to improve flywheel capacity. For example, flywheel bodies may be formed of carbon fiber material having a strength-to-weight ratio that is higher than the conventional metal materials. This permits rotation at higher speeds, such as up to approximately 60,000 rpm or more, thereby increasing energy storage capacity. The higher rotational speeds, however, may increase the amount of friction force and therefore decrease the efficiency of the flywheel assembly.

Some flywheel assemblies are known that use multiple flywheels to increase energy storage capacity. For example, U.S. Pat. No. 4,606,193 to Molina discloses a "Freewheel Flywheel Transmission System" having multiple freewheeling shafts coupled to an engine. An associated set of flywheels is directly connected to each freewheeling shaft, so that the flywheels in a given set rotate at the same speed. When a freewheeling shaft reaches a desired rotational speed, the next freewheeling shaft is engaged and brought up to speed. Once all of the freewheeling shafts are rotating at the desired speed, they are coupled to an alternator that is connected to an electric motor and a battery. While Molina discloses a system that uses multiple flywheels, it fails to consider parasitic loads, and resulting inefficiencies, associated with such a system.

## SUMMARY OF THE DISCLOSURE

In accordance with one aspect of the disclosure, a flywheel assembly is provided for a machine having an engine, wherein the flywheel assembly may include a flywheel input shaft operably coupled to the engine. A first flywheel may include a first flywheel housing, a first flywheel shaft rotatably supported by the first flywheel housing and configured for selective coupling to the flywheel input shaft, and a first flywheel body coupled to the first flywheel shaft, the first flywheel defining a first flywheel parasitic load profile. A second flywheel may include a second flywheel housing, a second flywheel shaft rotatably supported by the second flywheel housing and configured for selective coupling to the flywheel input shaft, and a second flywheel body coupled to the second flywheel shaft, the second flywheel defining a second flywheel parasitic load profile. A flywheel input clutch may be configured to selectively couple the first flywheel shaft to the flywheel input shaft, and a flywheel intermediate clutch may be configured to selectively couple the second flywheel shaft to the flywheel input shaft. A controller may be operably coupled to the flywheel input clutch and the fly-



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wheel intermediate clutch, and may be configured to determine a desired power output for the flywheel assembly, determine a desired first flywheel speed and a desired second flywheel speed associated with the desired power output, wherein the desired first flywheel speed and the desired second flywheel speed are selected based on the first flywheel parasitic load profile and the second flywheel parasitic load profile, respectively, and selectively actuate the flywheel input clutch and the flywheel intermediate clutch to rotate the first flywheel shaft at the desired first flywheel speed and the second flywheel shaft at the desired second flywheel speed.

In another aspect of the disclosure that may be combined with any of these aspects, a method is provided for controlling a flywheel assembly having a first flywheel defining a first flywheel parasitic load profile and a second flywheel defining a second flywheel parasitic load profile. The method may include determining a desired power output for the flywheel assembly and determining a desired first flywheel speed and a desired second flywheel speed sufficient to provide the desired power output, wherein the desired first flywheel speed is selected based on the first flywheel parasitic load profile and the desired second flywheel speed is selected based on the second flywheel parasitic load profile. The method may further include rotating the first flywheel at the desired first flywheel speed, and rotating the second flywheel at the desired second flywheel speed.

In another aspect of the disclosure that may be combined with any of these aspects, a machine may include a powertrain including an engine operatively coupled to a drivetrain, the drivetrain including a flywheel input shaft. A flywheel assembly may include a first flywheel including a first flywheel housing, a first flywheel shaft rotatably supported by the first flywheel housing and configured for selective coupling to the flywheel input shaft, and a first flywheel body coupled to the first flywheel shaft, the first flywheel defining a first flywheel parasitic load profile. The flywheel assembly may further include a second flywheel having a second flywheel housing, a second flywheel shaft rotatably supported by the second flywheel housing and configured for selective coupling to the flywheel input shaft, and a second flywheel body coupled to the second flywheel shaft, the second flywheel defining a second flywheel parasitic load profile. A flywheel input clutch may be configured to selectively couple the first flywheel shaft to the flywheel input shaft, and a flywheel intermediate clutch may be configured to selectively couple the second flywheel shaft to the flywheel input shaft. A controller may be operably coupled to the flywheel input clutch and the flywheel intermediate clutch, and may be configured to determine a desired power output for the flywheel assembly, determine a desired first flywheel speed and a desired second flywheel speed associated with the desired power output, wherein the first flywheel speed and the second flywheel speed are selected based on the first flywheel parasitic load profile and the second flywheel parasitic load profile, respectively, and selectively actuate the flywheel input clutch and the flywheel intermediate clutch to rotate the first flywheel shaft at the desired first flywheel speed and the second flywheel shaft at the desired second flywheel speed.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a side elevation view of a machine having a flywheel assembly according to the present disclosure.

FIG. 2 is a schematic illustration of an exemplary embodiment of a flywheel assembly in conjunction with a powertrain provided on the machine of FIG. 1.

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FIG. 3 is an enlarged schematic illustration of a flywheel used in the flywheel assembly of FIG. 2.

FIG. 4 is an enlarged schematic illustration of an alternative embodiment of a flywheel assembly according to the present disclosure.

FIG. 5 is a graphical illustration of a relationship between flywheel parasitic load and flywheel speed.

#### DETAILED DESCRIPTION

Embodiments of a flywheel assembly are disclosed for use with a machine having an engine. In some embodiments, the flywheel assembly may be used with a drivetrain configured to provide alternative points at which the flywheel may be connected to the drivetrain. For example, the drivetrain may be configured to allow the flywheel to be coupled both upstream and downstream of a transmission that may be operably coupled to the engine. The alternative connection points may increase flywheel efficiency during different modes of powertrain operation by allowing the operator to choose a connection point that minimizes mechanical loss for a given mode. In certain modes of operation, such as during initial “spin up” of the flywheel during start-up of the machine, it may be advantageous to directly connect the flywheel to the engine and bypass the transmission to reduce the amount of mechanical loss during such operation. In other modes of operation, such as during regenerative braking, it may be advantageous to directly connect the flywheel to the lower powertrain, again bypassing the transmission and associated mechanical loss. By providing a drivetrain that permits the flywheel to be connected at points both upstream and downstream of the transmission, the flywheel assembly may improve the overall efficiency of the flywheel during all modes of operation.

Other embodiments of a flywheel assembly and method are disclosed that may permit efficient operation of multiple flywheels by managing parasitic loads associated with the flywheels. As a flywheel rotates, it is subject to parasitic loads, such as friction, that reduce the amount of energy that can be stored by the flywheel. In systems using multiple flywheels, each flywheel has an associated parasitic load that is primarily related to the rotational speed of the flywheel. Based on parasitic load profiles of each flywheel, an efficient operation scheme may be employed that minimizes the overall parasitic load on the system. For example, it may be determined that operating a single flywheel at a high speed produces a parasitic load that is greater than an aggregate parasitic load produced by two flywheels operating at lower speeds. Based on the parasitic load profiles, desired flywheel speeds may be determined that reduce or minimize the overall parasitic load for a given power storage capacity.

FIG. 1 illustrates an exemplary machine 20. The machine 20 may be a mining truck, as shown, or any other type of machine, including on-highway machines, off-highway machines, earth moving equipment, generators, aerospace machines, locomotive machines, marine machines, or other engine powered applications. The machine 20 may include a chassis 22 and a powertrain 23 mounted on the chassis. The powertrain 23 may include a prime mover, such as an internal combustion engine 24, operably coupled to a drivetrain 25. The engine 24 may be any type of engine (internal combustion, gas, diesel, gaseous fuel, natural gas, propane, etc.), may be of any size, with any number of cylinders, and in any configuration (“V,” in-line, radial, etc.). In the illustrated embodiment, the engine 24 generates power that may be delivered by the drivetrain 25 to ground engaging members

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26. The ground engaging members 26 may be tires (as shown), tracks, or the like that may be suitable for a particular application.

The drivetrain 25 may mechanically couple the engine 24 to one or more of the ground engaging members 26. As schematically illustrated in FIG. 2, the drivetrain 25 may be configured for rear wheel drive. Accordingly, the drivetrain 25 may include a transmission 34 having a transmission input shaft 36 operably coupled to the engine 24 and a transmission output shaft 38. A lower powertrain 40 may have a lower powertrain input shaft 42 operably coupled to the transmission output shaft 38. In the illustrated embodiment, the lower powertrain may include a differential 44 operably coupled to a rear axle 46 which may provide a torque output to two rear ground engaging members 26. A transmission output clutch 48 is configured to selectively engage the transmission output shaft 38 to the lower powertrain input shaft 42. Additionally or alternatively, the drivetrain 25 may be configured for front or all wheel drive (not shown).

The drivetrain 25 may further include a bypass shaft 50 connected in parallel to the transmission input shaft 36 to provide a mechanical connection that bypasses the transmission 34. In the illustrated embodiment, the bypass shaft 50 may be coupled to a bypass gear 52 that engages a transmission input gear 54 coupled to the transmission input shaft 36. Accordingly, the bypass shaft 50 may be directly coupled to the engine 24 via the gears 52, 54, transmission input shaft 36, and the crankshaft 30.

A flywheel assembly 60 may be provided for storing energy from and/or discharging energy to the machine 20. As best shown in FIG. 3, the flywheel assembly 60 may include a first flywheel 64. The first flywheel 64 may include a first flywheel body 66 having a hub 68 and a rim 70. The hub 68 may be formed of a material, such as aluminum or steel, which is suitable for supporting the mass of the rim 70 when the first flywheel body 66 rotates at speeds of up to 60,000 rpm or more. The rim 70 may be formed of any suitable flywheel material, such as iron, steel, or carbon fiber. A first flywheel shaft 72 may be coupled to the hub 68 and supported for rotation by a first flywheel housing 74.

The first flywheel housing 74 may define a chamber 76 sized to receive the first flywheel body 66 and at least a portion of the first flywheel shaft 72. Bearings 78 may be coupled to opposite sides of the first flywheel housing 74 to journally support respective portions of the first flywheel shaft 72. Two shaft seals 81 may be disposed between opposite sides of the first flywheel housing 74 and the first flywheel shaft 72 to provide air tight seals. A vacuum pump (not shown) may fluidly communicate with the chamber 76 to generate a partial vacuum inside the first flywheel housing 74. The first flywheel 64 may further include a cooling system (not shown) to maintain the flywheel chamber 76 at a desirable operating temperature.

The flywheel assembly 60 may further include a continuously variable transmission (CVT) 80 for accommodating differences in rotational speeds of the flywheel and the drivetrain 25. A first CVT clutch 82 may be configured to selectively engage the CVT 80 with an upstream segment of the first flywheel shaft 72, while a second CVT clutch 84 may be configured to selectively engage the CVT 80 with a downstream segment of the first flywheel shaft 72. Alternatively, the CVT 80 may be replaced with other known mechanisms for interfacing between shafts rotating at different speeds. Still further, such structure may be completely eliminated by the use of other gearing in the drivetrain 25 that may sufficiently match the speeds of the flywheel and the drivetrain 25.

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The drivetrain 25 further may be configured so that the flywheel assembly 60 may be directly coupled to different points of the drivetrain 25 located upstream and downstream of the transmission 34. For example, a bypass clutch 86 may be configured to selectively engage the first flywheel shaft 72 to the bypass shaft 50, thereby to provide a direct mechanical connection between the first flywheel 64 and the engine 24. Additionally, a flywheel clutch 88 may be configured to selectively engage the first flywheel shaft 72 to the lower powertrain input shaft 42, thereby to provide a direct mechanical connection between the first flywheel 64 and the lower powertrain 40. In the illustrated embodiment, the flywheel clutch 88 may be a rotating-type clutch as shown, which permits the lower powertrain gear 92 to rotate freely on the lower powertrain input shaft 42 when the clutch is disengaged.

A controller, such as electronic control module (ECM) 94, may be provided to control operation of components provided on the machine 20. For example, the ECM 94 may be operably coupled to the engine 24, the transmission 34, the transmission output clutch 48, the CVT 80, the bypass clutch 86, and the flywheel clutch 88 to control operation of these components based on user inputs or feedback regarding operating parameters. The ECM 94 may include any components that may be used to run an application such as, for example, a memory, a secondary storage device, and a central processing unit. The ECM 94 may, however, contain additional or different components such as, for example, mechanical or hydromechanical devices. Various other known circuits may be associated with the ECM 94 such as, for example, power supply circuitry, signal-conditioning circuitry, solenoid driver circuitry, and other appropriate circuitry. While the ECM 94 is depicted in the drawings as a single controller, connected, multiple controllers may be used.

One or more feedback sensors may be provided for monitoring operating parameters of the machine 20. For example, a flywheel speed sensor 96 may be provided that is configured to sense a rotational speed of the first flywheel 64 and generate a flywheel speed signal. Additionally or alternatively, an engine speed sensor 98 may be provided that is configured to sense an engine speed and generate an engine speed signal, and a drivetrain speed sensor 100 may be provided that is configured to sense a rotational speed of a drivetrain component, such as the transmission 34, and generate a drivetrain speed signal. Still further, the command signal to the CVT 80 may be monitored for feedback.

The machine 20 may further include an auxiliary device that may be powered by the flywheel assembly 60. For example, a hydraulic pump 102 may be operably coupled to the first flywheel shaft 72. The hydraulic pump 102 may be used to operate any hydraulically powered system provided on the machine 20. The hydraulic pump 102 further may be operatively coupled to the ECM 94.

An input device 104, such as a user-engageable switch, may be located on the machine 20 to control a configuration of the drivetrain 25, as explained in greater detail below.

An alternative exemplary embodiment of a flywheel assembly 120 is illustrated in FIG. 4. A flywheel input clutch, such as a CVT 122, may be provided to accommodate differences in rotational speeds between the flywheel assembly 120 and a drivetrain (not shown). Accordingly, a first CVT clutch 124 may be configured to selectively engage the CVT 122 with a flywheel input shaft 126, while a second CVT clutch 128 may be configured to selectively engage the CVT 122 with a first flywheel shaft 130. The flywheel input shaft 126 may be operably coupled to an engine (not shown) by the drivetrain.

The flywheel assembly **120** may have multiple separate flywheels to increase the energy storage capacity of the system. In the exemplary embodiment illustrated in FIG. 4, the flywheel assembly **120** includes first and second flywheels **132**, **134**. While only two flywheels **132**, **134** are shown, it will be appreciated that the flywheel assembly **120** may include more than two flywheels without departing from the scope of this disclosure. The first flywheel **132** may include a first flywheel housing **136** configured to rotatably support the first flywheel shaft **130** (introduced above). A first flywheel body **138** may be coupled to the first flywheel shaft **130** and disposed in the first flywheel housing **136**. Similarly, the second flywheel **134** may include a second flywheel housing **140** rotatably supporting a second flywheel shaft **142**. A second flywheel body **144** may be coupled to the second flywheel shaft **142** and disposed in the second flywheel housing **140**.

The first and second flywheel shafts **130**, **142** may be selectively engaged to respectively rotate the first and second flywheel bodies **138**, **144** at desired speeds. In the illustrated embodiment, a flywheel intermediate clutch **146** is configured to selectively couple the first flywheel shaft **130** to the second flywheel shaft **142**.

In an alternative embodiment, the second flywheel **134** may be operated independently of the first flywheel **132**. For example, the drivetrain **25** may include mechanical components to form a second bypass (not shown) that connects the second flywheel shaft **142** to the output of the CVT **122** while bypassing the first flywheel shaft **130**. Accordingly, the second flywheel **134** may be rotated without requiring rotation of the first flywheel **132**.

An electric motor/generator **148** may be configured to provide energy to or draw energy from the flywheel assembly **120**. In the illustrated embodiment, the electric motor/generator **148** includes a motor/generator shaft **150**. A motor/generator clutch **152** may be provided to selectively couple the motor/generator shaft **150** to the second flywheel shaft **142**. The electric motor/generator **148** may draw power from the flywheel assembly **120** to operate auxiliary systems, or may provide power to the flywheel assembly **120** to initiate or maintain desired rotational speeds of the first and/or second flywheels **132**, **134**.

A controller, such as an ECM **154**, may be operatively coupled to the CVT **122**, the first and second CVT clutches **124**, **128**, the flywheel intermediate clutch **146**, the motor/generator clutch **152**, and the motor/generator **148**. The ECM **154** may be configured to send signals to each of these devices. Additionally, the ECM **154** may be configured to receive feedback from the devices. The ECM **154** further may be configured to operate the coupled devices, as discussed in greater detail below.

#### INDUSTRIAL APPLICABILITY

Certain of the exemplary embodiments of flywheel assemblies and methods may be advantageously employed on machines having ground engaging members. The flywheel assembly **60** may be coupled to a drivetrain **25** that may selectively allow the flywheel assembly **60** to be directly connected both upstream and downstream of a transmission **34**. Such a drivetrain arrangement may increase efficiency of the flywheel assembly **60** in multiple modes of operation.

More specifically, the ECM **94** may be configured to operate the drivetrain **25** in multiple alternative modes. Some of the modes may provide a direct mechanical connection path between the flywheel assembly **60** and the engine **24**. For example, in a flywheel spin up mode, the flywheel assembly **60** may be brought to a desired rotational speed prior to

rotating the ground engaging members **26**. In the flywheel spin up mode, the bypass clutch **86** may be engaged, the transmission output clutch **48** may be disengaged, and the flywheel clutch **88** may be disengaged. With the drivetrain **25** configured in this manner, the first flywheel shaft **72** may be directly connected to the engine **24** through the bypass clutch **86**, bypass shaft **50**, and transmission input shaft **36**. By mechanically connecting the flywheel assembly **60** upstream of the transmission **34**, thereby bypassing the transmission **34**, mechanical losses between the engine **24** and flywheel assembly **60** may be reduced and therefore power output from the engine **24** may be more efficiently captured by the flywheel assembly **60**. The transmission output shaft **38** may be decoupled from the lower powertrain **40** by the disengaged transmission output clutch **48** and the first flywheel shaft **72** may be decoupled from the lower powertrain **40** by the disengaged flywheel clutch **88**, so the machine **20** may not travel during initial spin up mode.

The spin up mode configuration of the drivetrain **25** may also assist with engine starting or restarting. During engine starting or restarting, power from the flywheel assembly **60** may be provided to the engine **24**. The flywheel assembly **60** may already have a sufficient amount of stored kinetic energy, such as when the flywheel assembly **60** is still rotating from previous machine operation. Alternatively, another source of power, such as the electric motor/generator **148** of the embodiment shown in FIG. 4, may be used to first rotate the flywheel assembly to a sufficient speed before engaging the bypass clutch **86**, thereby to provide power to the engine **24**.

An alternative mode using a direct mechanical connection path between the flywheel assembly **60** and the engine **24** may be a load leveling mode, in which power from the flywheel assembly **60** may be used to assist power output from the engine **24**. In the load leveling mode, the bypass clutch **86** may be engaged, the transmission output clutch **48** may be engaged, and the flywheel clutch **88** may be disengaged. With the drivetrain **25** configured in this manner, power from the flywheel assembly **60** may directly assist power from the engine **24** to rotate the transmission input shaft **36**. As a result, the engine **24** may be sized for less than peak power capacity since the flywheel assembly **60** may be used to assist with high load conditions.

Other drivetrain modes may provide a direct mechanical connection path between the flywheel assembly **60** and the lower powertrain **40**. For example, the ECM **94** further may be configured to operate the drivetrain **25** in a regeneration mode, during which the flywheel assembly **60** receives power from braking applied to the ground engaging members **26**. In the regeneration mode, the bypass clutch **86** may be disengaged, the transmission output clutch **48** may be disengaged, and the flywheel clutch **88** may be engaged. With the drivetrain **25** configured in this manner, the first flywheel shaft **72** may be directly connected to the ground engaging members **26** through the lower powertrain input shaft **42**, differential **44**, and the rear axle **46**. By mechanically connecting the flywheel assembly **60** downstream of the transmission **34**, thereby bypassing the transmission **34**, mechanical losses between the ground engaging members **26** and the flywheel assembly **60** may be reduced and therefore power generated by braking may be more efficiently captured by the flywheel assembly.

An alternative mode using a direct mechanical connection path between the flywheel assembly **60** and the lower powertrain **40** may be an acceleration mode, in which power from the flywheel assembly **60** is used to assist power from the transmission output shaft **38** to rotate the lower powertrain **40**. In the acceleration mode, the bypass clutch **86** may be dis-

gaged, the transmission output clutch **48** may be engaged, and the flywheel clutch **88** may be engaged. With the drivetrain **25** configured in this manner, power from the flywheel assembly **60** may directly assist power from the transmission **34** to rotate the ground engaging members **26**.

The ECM **94** further may be configured to operate the drivetrain **25** in an auxiliary power mode, during which an auxiliary device (such as the hydraulic pump **102**) may be operated by the flywheel assembly **60**. In the auxiliary power mode, each of the bypass clutch **86**, transmission output clutch **48**, and flywheel clutch **88** may be disengaged, so that only the auxiliary device is coupled to the flywheel assembly **60**. By isolating the other drivetrain components, mechanical losses are again reduced and therefore power is more efficiently output from the flywheel to the hydraulic pump **102**. Additionally, the auxiliary device may be operated with the engine **24** turned off.

By providing a drivetrain **25** having alternative modes of operation to connect the flywheel assembly **60** either upstream or downstream of the transmission **34**, the flywheel assembly **60** may more efficiently store and release power as desired.

In other exemplary embodiments, flywheel assemblies and methods are provided that may increase efficiency when using multiple separate flywheels. According to certain embodiments, a control scheme may be used to reduce the amount of parasitic load acting on the assembly.

The parasitic load of a flywheel may indicate an aggregate of forces that resist rotation of the flywheel. Accordingly, components of a parasitic load on a flywheel may include mechanical friction loss between bearings and the flywheel shaft, air friction loss generated as the flywheel body rotates inside the housing, and other forces that resist rotation of the flywheel. For a given flywheel, the parasitic load may be generally related to the speed at which the flywheel rotates, with the parasitic load generally increasing as rotational speed increases. Accordingly, a given flywheel may have a parasitic load profile that may be expressed as a magnitude of the parasitic load (which may be measured in kilowatts of energy dissipation) versus rotational speed (which may be measured in rpm). For example, the first flywheel **132** may have a first flywheel parasitic load profile **156** while the second flywheel **134** may have a second flywheel parasitic load profile **158**, as shown in graph form in FIG. 5.

The ECM **154** may be configured to operate the first and second flywheels **132**, **134** at speeds that reduce or minimize the overall parasitic load of the flywheel assembly **120**. For example, the ECM **154** may be configured to determine a desired first flywheel speed and a desired second flywheel speed associated with a desired power output for the flywheel assembly **120**. The first flywheel speed and the second flywheel speed may be selected based on the first flywheel parasitic load profile **156** and the second flywheel parasitic load profile **158**. The ECM **154** may then selectively actuate the CVT **122** and the flywheel intermediate clutch **146** to rotate the first flywheel shaft **130** at the desired first flywheel speed and the second flywheel shaft **142** at the desired second flywheel speed.

More specifically, when determining the first flywheel speed, the ECM **154** may determine a first flywheel friction loss associated with rotation of the first flywheel body **138** at the desired first flywheel speed based on the first flywheel parasitic load profile **156**. Similarly, when determining the second flywheel speed, the ECM **154** may determine a second flywheel friction loss associated with rotation of the second flywheel body **144** at the desired second flywheel speed based on the second flywheel parasitic load profile **158**. The ECM

**154** may be configured to select the first and second flywheel speeds such that an aggregate of the first and second flywheel friction losses is reduced or minimized.

The flywheels may be selected to have different characteristics, based on expected usage. For example, use of the second flywheel **134** may be intermittent, such as during peak engine loads or as a power source for auxiliary devices when the engine **24** is off. Accordingly, the second flywheel **134** may normally be stationary, or rotated at relatively low speeds, subject to periodic use at operational speeds. As a result, the second flywheel **134** may be configured for a lighter duty cycle, which would permit the use of lighter duty components that cause a lower parasitic load. In such a system, the ECM **154** may be configured to rotate the second flywheel **134** only when a peak demand is expected or encountered, or when auxiliary device use is needed when the engine **24** is off. In the latter instance, the use of the lighter duty cycle flywheel will minimize losses due to parasitic load, thereby allowing longer use of auxiliary devices with the engine **24** off.

It will be appreciated that the foregoing description provides examples of the disclosed assembly and technique. However, it is contemplated that other implementations of the disclosure may differ in detail from the foregoing examples. All references to the disclosure or examples thereof are intended to reference the particular example being discussed at that point and are not intended to imply any limitation as to the scope of the disclosure more generally. All language of distinction and disparagement with respect to certain features is intended to indicate a lack of preference for those features, but not to exclude such from the scope of the disclosure entirely unless otherwise indicated.

Recitation of ranges of values herein are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context.

Accordingly, this disclosure includes all modifications and equivalents of the subject matter recited in the claims appended hereto as permitted by applicable law. Moreover, any combination of the above-described elements in all possible variations thereof is encompassed by the disclosure unless otherwise indicated herein or otherwise clearly contradicted by context.

What is claimed is:

1. A flywheel assembly for a machine having an engine, the flywheel assembly comprising:
  - a flywheel input shaft operably coupled to the engine;
  - a first flywheel including a first flywheel housing, a first flywheel shaft rotatably supported by the first flywheel housing and configured for selective coupling to the flywheel input shaft, and a first flywheel body coupled to the first flywheel shaft, the first flywheel defining a first flywheel parasitic load profile expressed as a magnitude of a first external parasitic load acting on the first flywheel versus a rotational speed of the first flywheel;
  - a second flywheel including a second flywheel housing, a second flywheel shaft rotatably supported by the second flywheel housing and configured for selective coupling to the flywheel input shaft, and a second flywheel body coupled to the second flywheel shaft, the second flywheel defining a second flywheel parasitic load profile expressed as a magnitude of a second external parasitic

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load acting on the second flywheel versus a rotational speed of the second flywheel;

a flywheel input clutch configured to selectively couple the first flywheel shaft to the flywheel input shaft;

a flywheel intermediate clutch configured to selectively couple the second flywheel shaft to the flywheel input shaft; and

a controller operably coupled to the flywheel input clutch and the flywheel intermediate clutch, the controller configured to:

determine a desired power output for the flywheel assembly;

determine a desired first flywheel speed based on the first flywheel parasitic load profile;

determine a desired second flywheel speed based on the second flywheel parasitic load profile;

wherein the desired first and second flywheel speeds are selected to be sufficient to provide the desired power output while minimizing an aggregate of the magnitude of the first external parasitic load acting on the first flywheel and the magnitude of the second external parasitic load acting on the second flywheel; and

selectively actuate the flywheel input clutch and the flywheel intermediate clutch to rotate the first flywheel shaft at the desired first flywheel speed and the second flywheel shaft at the desired second flywheel speed.

2. The flywheel assembly of claim 1, wherein the controller is further configured to:

determine a first flywheel friction loss associated with rotation of the first flywheel body at the desired first flywheel speed based on the first flywheel parasitic load profile; and

determine a second flywheel friction loss associated with rotation of the second flywheel body at the desired second flywheel speed based on the second flywheel parasitic load profile.

3. The flywheel assembly of claim 2, wherein the controller is further configured to minimize an aggregate of the first flywheel friction loss and the second flywheel friction loss.

4. The flywheel assembly of claim 1, further including:

a motor/generator having a motor/generator input shaft; and

a motor/generator clutch configured to selectively couple the motor/generator input shaft to the second flywheel shaft;

wherein the controller is operably coupled to the motor/generator clutch.

5. The flywheel assembly of claim 1, wherein the first flywheel parasitic load profile is different from the second flywheel parasitic load profile.

6. The flywheel assembly of claim 1, wherein the desired first flywheel speed is zero.

7. The flywheel assembly of claim 1, wherein the desired second flywheel speed is zero.

8. The flywheel assembly of claim 1, wherein the desired first flywheel speed is different from the desired second flywheel speed.

9. The flywheel assembly of claim 1, in which the flywheel intermediate clutch is configured to selectively engage the first flywheel shaft to the second flywheel shaft.

10. A method of controlling a flywheel assembly including a first flywheel defining a first flywheel parasitic load profile expressed as a magnitude of a first external parasitic load acting on the first flywheel versus a rotational speed of the first flywheel, and a second flywheel defining a second flywheel parasitic load profile expressed as a magnitude of a

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second external parasitic load acting on the second flywheel versus a rotational speed of the second flywheel, the method comprising:

determining a desired power output for the flywheel assembly;

determining a desired first flywheel speed based on the first flywheel parasitic load profile;

determining a desired second flywheel speed based on the second flywheel parasitic load profile;

wherein the desired first and second flywheel speeds are selected to be sufficient to provide the desired power output while minimizing an aggregate of the magnitude of the first external parasitic load acting on the first flywheel and the magnitude of the second external parasitic load acting on the second flywheel;

rotating the first flywheel at the desired first flywheel speed; and

rotating the second flywheel at the desired second flywheel speed.

11. The method of claim 10, further including:

determining from the first flywheel parasitic load profile a first flywheel friction loss associated with rotation of the first flywheel body at the desired first flywheel speed; and

determining from the second flywheel parasitic load profile a second flywheel friction loss associated with rotation of the second flywheel body at the desired second flywheel speed.

12. The method of claim 11, wherein determining the desired first flywheel speed and the desired second flywheel speed is based on minimizing an aggregate of the first flywheel friction loss and the second flywheel friction loss.

13. The method of claim 10, wherein the desired first flywheel speed is zero.

14. The method of claim 10, wherein the desired second flywheel speed is zero.

15. The method of claim 10, wherein the desired first flywheel speed is different from the desired second flywheel speed.

16. A machine comprising:

a powertrain including an engine operatively coupled to a drivetrain, the drivetrain including a flywheel input shaft;

a flywheel assembly including:

a first flywheel including a first flywheel housing, a first flywheel shaft rotatably supported by the first flywheel housing and configured for selective coupling to the flywheel input shaft, and a first flywheel body coupled to the first flywheel shaft, the first flywheel defining a first flywheel parasitic load profile expressed as a magnitude of a first external parasitic load acting on the first flywheel versus a rotational speed of the first flywheel;

a second flywheel including a second flywheel housing, a second flywheel shaft rotatably supported by the second flywheel housing and configured for selective coupling to the flywheel input shaft, and a second flywheel body coupled to the second flywheel shaft, the second flywheel defining a second flywheel parasitic load profile expressed as a magnitude of a second external parasitic load acting on the second flywheel versus a rotational speed of the second flywheel;

a flywheel input clutch configured to selectively couple the first flywheel shaft to the flywheel input shaft; and

a flywheel intermediate clutch configured to selectively couple the second flywheel shaft to the flywheel input shaft; and

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a controller operably coupled to the flywheel input clutch and the flywheel intermediate clutch, the controller configured to:

determine a desired power output for the flywheel assembly;

determine a desired first flywheel speed based on the first flywheel parasitic load profile;

determine a desired second flywheel speed based on the second flywheel parasitic load profile;

wherein the desired first and second flywheel speeds are selected to be sufficient to provide the desired power output while minimizing an aggregate of the magnitude of the first external parasitic load acting on the first flywheel and the magnitude of the second external parasitic load acting on the second flywheel; and

selectively actuate the flywheel input clutch and the flywheel intermediate clutch to rotate the first flywheel shaft at the desired first flywheel speed and the second flywheel shaft at the desired second flywheel speed.

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**17.** The machine of claim **16**, wherein the controller is further configured to:

determine a first flywheel friction loss associated with rotation of the first flywheel body at the desired first flywheel speed based on the first flywheel parasitic load profile; and

determine a second flywheel friction loss associated with rotation of the second flywheel body at the desired second flywheel speed based on the second flywheel parasitic load profile.

**18.** The machine of claim **17**, wherein the controller is further configured to minimize an aggregate of the first flywheel friction loss and the second flywheel friction loss.

**19.** The machine of claim **16**, wherein the first flywheel parasitic load profile is different from the second flywheel parasitic load profile.

**20.** The machine of claim **16**, in which the flywheel intermediate clutch is configured to selectively engage the first flywheel shaft to the second flywheel shaft.

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